MODULATING ION BEAM CURRENT

FIELD OF THE INVENTION

The present invention relates generally to ion implantation systems, and more particularly to modulating ion beam current in such systems to attain more uniform ion implantations.

BACKGROUND OF THE INVENTION

Ion implantation systems are used to impart impurities, known as dopant elements, into semiconductor substrates or wafers, commonly referred to as workpieces. In such systems, an ion source ionizes a desired dopant element, and the ionized impurity is extracted from the ion source as a beam of ions. The ion beam is directed (*e.g.*, swept) across respective workpieces to implant ionized dopants within the workpieces. The dopant ions alter the composition of the workpieces causing them to possess desired electrical characteristics, such a may be useful for fashioning particular semiconductor devices, such as transistors, upon the substrates.

The continuing trend toward smaller electronic devices has presented an incentive to “pack” a greater number of smaller, more powerful and more energy efficient semiconductor devices onto individual wafers. This necessitates careful control over semiconductor fabrication processes, including ion implantation and more particularly the uniformity of ions implanted into the wafers. Moreover, semiconductor devices are being fabricated upon larger workpieces to increase product yield. For example, wafers having a diameter of 300 mm or more are being utilized so that more devices can be produced on a single wafer. Such wafers are expensive and, thus, make it very desirable to mitigate waste, such as having to scrap an entire wafer due to non-uniform ion implantation. Larger wafers make

uniform ion implantation challenging, however, since ion beams have to be scanned across larger angles and distances to reach the perimeters of the wafers. Scanning a beam over such larger angles and distances can cause variations in the flux of the beam that can lead to non-uniform implantation.

SUMMARY OF THE INVENTION

The following presents a simplified summary in order to provide a basic understanding of one or more aspects of the invention. This summary is not an extensive overview of the invention, and is neither intended to identify key or critical elements of the invention, nor to delineate the scope thereof. Rather, the primary purpose of the summary is to present some concepts of the invention in a simplified form as a prelude to the more detailed description that is presented later.

The present invention is directed to modulating ion beam current in an ion implantation system to mitigate non-uniform ion implantations, for example. Multiple arrangements are disclosed for modulating the intensity of the ion beam. For example, the volume or number of ions within the beam is altered by biasing one or more different elements downstream of the ion source. Similarly, the dosage of ions within the ion beam can also be manipulated by controlling elements more closely associated with the ion source. In this manner, the implantation process can be regulated so that the wafer is coated with a more uniform concentration of ions.

According to one or more aspects of the present invention, an ion implantation system suitable for use in implanting ions into one or more workpieces is disclosed. The system includes an ion source for producing a quantity of ions that can be extracted in the form of an ion beam having a beam current. The system also includes a beamline assembly downstream of the ion source to receive and direct the beam of ions. An end station downstream of the beamline assembly is also included to hold the one or more workpieces toward which the ion beam is directed. Finally,

the system includes a component associated with or downstream of the ion source for modulating the ion beam current.

In accordance with one or more other aspects of the present invention, an acceleration system suitable for use in implanting ions into a workpiece is disclosed. The system includes an ion source for producing a quantity of ions that can be extracted in the form of an ion beam, the ion beam having a beam current. The system also includes a beamline assembly downstream of the ion source to receive and direct the beam of ions. An end station downstream of the beamline assembly is also included to hold one or more workpieces onto which the ion beam is directed. Finally, the system includes a first modulating component associated with the ion source for modulating the beam current.

To the accomplishment of the foregoing and related ends, the following description and annexed drawings set forth in detail certain illustrative aspects and implementations of the invention. These are indicative of but a few of the various ways in which the principles of the invention may be employed. Other aspects, advantages and novel features of the invention will become apparent from the following detailed description of the invention when considered in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic block diagram illustrating components of an ion implantation system according to one or more aspects of the present invention to modulate ion beam current.

Fig. 2 is a cross sectional side view illustrating an exemplary ion implantation system in accordance with one or more aspects of the present invention.

Fig. 3 is a schematic block diagram illustrating particular components of an ion implantation system wherein one or more aspects of the present invention are

implemented;

Fig. 4 is a top view of an ion implantation system wherein one or more aspects of the present invention are implemented to modulate ion beam current;

Fig. 5 is a graphical representation depicting a relationship between changes in an extraction suppression voltage and changes in ion beam current; and

Fig. 6 is another graphical representation illustrating a relationship between changes in an extraction suppression voltage and changes in ion beam current.

DETAILED DESCRIPTION OF THE INVENTION

The present invention will now be described with reference to the drawings wherein like reference numerals are used to refer to like elements throughout. The illustrations and following descriptions are exemplary in nature, and not limiting. Thus, it will be appreciated that variants of the illustrated systems and methods and other such implementations apart from those illustrated herein are deemed as falling within the scope of the present invention and the appended claims.

The present invention relates to modulating ion beam current in an ion implantation system to mitigate non-uniform ion implantations, for example. Multiple arrangements are revealed for modulating the intensity of the ion beam. For example, the volume or number of ions within the beam is altered by biasing one or more different elements downstream of the ion source. Alternatively, the dosage of ions within the ion beam can also be manipulated by controlling elements more closely associated with the ion source. In this manner, the implantation process can be regulated so that the concentration of ions implanted into the wafer is substantially uniform across the wafer.

Referring initially to Fig. 1, an ion implantation system 100 suitable for implementing one or more aspects of the present invention is depicted in block diagram form. The system 100 includes an ion source 102 for producing a quantity

of ions that can be extracted in the form of an ion beam 104. The ion source 102 generally includes a gas source 106 from which the ions are generated, and a power source 108 that facilitates the production of the ions from the gas.

A beamline assembly 110 is provided downstream of the ion source 102 to receive the ion beam 104. The beamline assembly 110 in one example includes, among other things, a mass analyzer 112. The beamline assembly 110 is situated along the path to receive the beam 104. The mass analyzer 112 includes a field generating component, such as a magnet 114, and operates to provide a field across the beam path 104 so as to deflect ions from the ion beam 104 at varying trajectories according to mass (*e.g.*, charge to mass ratio). Ions traveling through the magnetic field experience a force that directs individual ions of a desired mass along the beam path 104 and deflects ions of undesired mass away from the beam path.

The ion implantation system 100 further includes an end station 116 to receive the mass analyzed ion beam 104 from the beamline assembly 110. The end station 116 supports one or more workpieces such as semiconductor wafers (not shown) along the beam path for implantation using the mass analyzed ion beam 104. The end station 116 includes a target scanning system 118 for translating or scanning one or more target workpieces and the ion beam 104 relative to one another. The target scanning system 118 may provide for batch or serial implantation, for example, as may be desired under given circumstances, operating parameters and/or objectives.

Additionally, a measurement component 120 is operatively coupled to the end station 116. The measurement component may include, for example, a Faraday cup (not shown) that is operable to detect the intensity of the ion beam as the beam is scanned across the wafer. According to one or more aspects of the present invention, the detected current density is fed back (*e.g.*, *via* a processor - not shown) to control one or more beam current modulation components 122, 124. In

accordance with one or more aspects of the present invention, one or more of the components 122, 124 can be closely associated with the ion source 102 and/or be situated downstream from the ion source 102 (*e.g.*, on the beamline assembly 110 or end station 116).

The ion implantation system 100 may also include a mechanism 126 in front of the end station 116 to scan the ion beam 104 relative to the one or more workpieces. Such mechanisms may, for example, be electric and/or magnetic. For example, the mechanism may include one or more electrically conductive plates that can be biased to have an electromagnetic field controllably developed there-across. The field lines influence the direction of the ion beam 104 passing there-through, and can be selectively controlled to cause the beam 104 to scan across the workpieces in a desired manner.

Referring now to Fig. 2, an exemplary ion implantation system 200 suitable for implementing one or more aspects of the present invention is depicted in somewhat greater detail. Note that although the system in Fig. 2 illustrates a low energy system, it should be appreciated that the system 200 is provided as an example, and that the present invention finds utility in various types of ion implantation systems, and such variations are contemplated as falling within the scope of the present invention. The system 200 includes an ion source 202, a beamline assembly 204, and a target or end station 206. An expansible stainless steel bellows assembly 208, which permits movement of the end station 206 with respect to the beamline assembly 204, connects the end station 206 and the beamline assembly 204.

The ion source 202 comprises a plasma chamber 210 and an ion extraction assembly 212. Energy is imparted to an ionizable dopant gas to generate ions within the plasma chamber 210. Generally, positive ions are generated, although the present invention is applicable to systems wherein negative ions are generated by the source 202. The positive ions are extracted through a slit in the plasma chamber

210 by the ion extraction assembly 212, which comprises a plurality of electrodes 214. Accordingly, the ion extraction assembly 212 functions to extract a beam 216 of positive ions from the plasma chamber 210 and to accelerate the extracted ions into the beamline assembly 204, and more particularly into a mass analysis magnet 218 within the beamline assembly 204.

The mass analysis magnet 218 includes a curved beam path 220 within a passageway 222 defined by a metal (*e.g.*, aluminum) beam guide having side-walls 224, evacuation of which is provided by a vacuum pump 226. The ion beam 216 that propagates along this path 220 is affected by the magnetic field generated by the mass analysis magnet 218, to reject ions of an inappropriate charge-to-mass ratio. Control electronics 228 are included to adjust the strength and orientation of this dipole magnetic field, among other things. The magnetic field is controlled by the electrical current through the field windings of the magnet 218 through a magnet connector 230. It will be appreciated that control electronics 228 may include a processor and/or computer system for overall control of the system 200 (*e.g.*, by an operator).

The dipole magnetic field causes the ion beam 216 to move along the curved beam path 220 from a first or entrance trajectory 232 near the ion source 202 to a second or exit trajectory 234 near an exiting end of the passageway 222. Portions 236 and 238 of the beam 216, comprised of ions having an inappropriate charge-to-mass ratio, are deflected away from the curved trajectory and into the beam guide side walls 224. In this manner, the magnet 218 only allows those ions in the beam 220 which have the desired charge-to-mass ratio to traverse entirely through the passageway 222.

The beamline assembly 204 can also be said to include an accelerator 240. The accelerator 240 includes a plurality of electrodes 242 arranged and biased to accelerate and/or decelerate ions, as well as to focus, bend and decontaminate the

ion beam. A dosimetry indicator such as a Faraday cup 244 may also be included to detect a sample current of the ion beam. A source of plasma 246 may also be included to provide a plasma shower 248 for neutralizing a (positive) charge that would otherwise accumulate on a target workpiece as a result of being implanted by the (positively) charged ion beam 216. A vacuum pump 250 may further be included to evacuate the accelerator 240.

Downstream of the accelerator 240 is the end station 206, which includes a support 252 upon which one or more wafers 254 or other workpieces to be treated are mounted. The wafer support 252 resides in a target plane that is generally oriented relatively perpendicularly to the direction of the implant beam, although the wafer support may also be oriented at angles substantially different from that shown and described. Wafer support may also, for example, take the form of a mechanical arm capable of moving a wafer through the beam or a rotating disk. Fig. 2 illustrates a disc shaped wafer support 252 that is rotated by a motor 256 at the end station 206. The ion beam thus strikes wafers mounted to the support as they move in a circular path. The end station 206 pivots about point 258, which is the intersection of the path 260 of the ion beam and the wafer 254, so that the target plane is adjustable about this point 258.

It will be appreciated that the Faraday cup 244 can be utilized in mapping the ion implantation on one or more wafers. For example, the cup 244 can be effectively substituted for the one or more wafers during a test run. The ion beam and Faraday cup 244 can then be moved relative to one another while the beam current is held constant. In this manner, variations in ion dosage (*e.g.*, that may occur at the perimeters of the wafers) can be detected. A waveform or map of beam current intensity versus scan position can thus be identified (*e.g.*, by feeding the readings taken by the cup back to the control electronics 228). The detected waveform(s) can then be utilized to adjust the beam current during actual implantation. For example,

the beam current can be adjusted upward as the beam approaches the perimeters of the wafers and/or may correspondingly be reduced as the beam implants into more centralized locations on the wafers.

Additionally, during actual implantation, the Faraday cup 244 can be utilized to take readings of beam intensity just as the beam finishes respective scans (*e.g.*, so that the cup 244 does not interfere with the implantations). These readings can then be compared to the waveforms to determine just how much the beam current should be ramped up (or down) to comport with the waveforms. It will be appreciated that such end of scan measurements can be done continuously or intermittently to mitigate non-uniform ion implantations. It will be further appreciated that a biasing voltage applied to the extraction assembly 212 can, for example, be varied to adjust the beam current density. Similarly, the source of plasma 246 can be adjusted to vary (*e.g.*, the intensity) a plasma shower 248 in accordance with one or more aspects of the present invention.

In the example illustrated, a scanning mechanism is also included in the beamline assembly 204 to facilitate maneuvering the beam 216 relative to the one or more wafers 254. In one arrangement, the mechanism may include, for example, two or more electrically conductive plates 272, 274 positioned so that the ion beam 216 passes there-through. The electrodes 272, 274 can be selectively biased with a potential to deflect the ion beam 216 in a prescribed manner. Similarly, the scanning mechanism may include a plurality of electromagnets (not shown) that may be energized to produce magnetic lines of flux there-between to selectively deflect the beam in a prescribed manner.

Fig. 3 illustrates in schematic block diagram form certain components of an ion implantation system 300 wherein one or more aspects of the present invention are implemented. The system 300 includes an ion source 302 for generating a source of ions. In the example shown, the ion source 302 includes a cathode 304, an anode

306, a mirror electrode 308, a gas supply 310 and source magnet components 312a, 312b. A power supply 314 and an arc power supply 316 are operatively coupled to the cathode 304, and another supply 318 is also connected to the source magnet components 312a, 312b in the example shown.

In operation, the gas supply 310 provides one or more precursor gases (*e.g.*, *via* a conduit 320) into an area 322 of the source 302 wherein the ions are generated. The cathode 304, in one example, takes the form of a filament (*e.g.*, a rod made of tungsten or tungsten alloy) is heated by the power supply 314 (*e.g.*, to about 2000 degrees Kelvin) to excite electrons therein. The arc supply 316, in turn, provides additional energy to the cathode 304 (*e.g.*, to heat the cathode to about 2800 degrees Kelvin) to cause electrons to jump from the cathode 304 into the area 322 wherein the gas is situated. The anode 306 assists with drawing the electrons into area 322, and may include sidewalls (not shown) of the ion source 302, for example. Further, supply 314 may also be coupled to the anode 306 so that a bias can be set up between the cathode 304 and the anode 306 to facilitate drawing the electrons into area 322.

The mirror electrode 308 assists with maintaining the electrons within area 322. In particular, a bias imparted to the mirror electrode 308 serves to repel electrons emitted from the cathode 304 back into area 322. Similarly, a magnetic field induced within the ion source 302 by the source magnet serves to maintain electrons within area 322 and off of sidewalls (not shown) of the source 302. In the example shown, two components 312a and 312b of the source magnet are shown. These may be indicative, of a cross-sectional view of windings and/or a yoke of an electromagnet, for example. The electrons moving around within area 322 collide with the gaseous molecules within area 322 to create the ions. In particular, electrons that collide with gaseous molecules with sufficient force cause one or more electrons to become dislodged from the molecules, thus producing positively charged

gaseous ions. It will be appreciated that the magnetic field applied by the source magnet may be parallel to the cathode to increase the electron path length and to assist with suspending a plasma of both ions and electrons within area 322.

It will be further appreciated that the present invention contemplates and has application to negatively charged ions also. Additionally, it will also be appreciated that the beam current density or intensity is related to the number of ions produced in the ion source 302. Thus, in accordance with one or more aspects of the present invention, any one or more of the components of the ion source can be selectively adjusted to modulate the beam current. By way of example only and not limitation, the magnetic field set up by the source magnet 312 can be altered by controlling the supply 318 to increase or retard the number of ions generated within the source 302 to correspondingly increase or decrease the beam current. Modulating the beam current *via* the source magnet may be more effective at higher energies (*e.g.*, where the magnetic field is around 200 Gauss) since beam currents may have a heightened (*e.g.*, non-linear) sensitivity to changes introduced by the supply 318 at lower energies.

It will be further appreciated that the present invention contemplates and has application to ion sources of types other than the arc discharge source described above. For example, an ion source may include a means of RF excitation to produce ions. Such a source is disclosed in U.S. Patent 5,661,308, the entirety of which is hereby incorporated by reference. An additional example is an ion source that may include a means of excitation by electron beam injection to produce ions. This is sometimes referred to as a "soft ionization" type of source. An example of such a source is disclosed in U.S. Patent 6,452,338, the entirety of which is also hereby incorporated by reference. An additional example of an ion source to which the present invention has application is an ion source that includes a means of microwave excitation to produce a plurality of ions.

The ion beam 326 is extracted from the ion source 302 by electrodes 330 which are generally biased negatively with respect to the ion source 302. In addition to extracting ions from the ion source, electrodes 330 also serve the function of providing suppression of electrons which are attracted to the ion source 302 by its generally positive bias. Further on, the beam 326 encounters ground electrodes 332 and a subsequent aperture defined by plates 334 before entering the beamguide 336 and associated analyzer magnet 338. After being separated according to a desired mass-to-charge ratio in the beamguide 336 and analyzer magnet 338, the beam 326 then encounters another set of electrodes 340 before entering a resolving aperture defined by plates 342 that further separates out undesired species of ions. The beam 326 then encounters yet another set of electrodes 344 before being bathed in a plasma to neutralize space charge and neutralize charge build-up that would otherwise accumulate on a target workpiece. The beam 326 then impinges upon one or more workpieces (not shown) located within an end station 346.

It will be appreciated that the beam current may be affected by many of the components of the system 300. For example, respective biases on the extraction suppression electrodes 330, ground electrodes 332, plates 334, electrodes 340, plates 342 and electrodes 344 can affect the beam current. Accordingly, the beam current can be modulated by selectively controlling one or more of the extraction suppression supply 350, floating ground supply 352, supply 354, supply 356, supply 358 and supply 360 which control the respective voltages applied to these components. It will be appreciated that while a combined set of extraction suppression electrodes 330 are discussed herein, the present invention contemplates separate sets of extraction and suppression electrodes having respective supplies that can be independently varied to alter the respective voltages applied to those electrodes. It will be further appreciated that the ground electrodes 332 are generally modulated with a voltage different from, but approximately zero, on

average. This distinguishes the ground electrodes 332 from a general case of an electrode which may have some non-zero bias.

The foregoing supplies can be controlled by a controller 364, for example, that takes readings from a measurement system 368 (*e.g.*, that includes a Faraday cup) indicative of end of scan beam current during ion implantation, for example. Similarly, the controller can be operatively coupled to the source of neutralization plasma 370 to modulate the beam current by selectively regulating the amount of active plasma to which the beam 326 is exposed. Modulating the beam current *via* the source of plasma 370 may be more effective at lower energies (*e.g.*, less than about 10 keV) since active plasma neutralization is typically not required for efficient beam transport at higher energies. It will be appreciated that the controller may also assist (*e.g.*, the measurement system 368) in developing implantation waveforms as previously discussed, and may make use of such waveforms in facilitating selective adjustments to the beam current.

It will be appreciated that the beam current can be modulated at one or more particular frequencies (*e.g.*, in the range of about 1 – 1000 Hz) or over one or more dynamic ranges (*e.g.*, of about 10-20% of the beam current). The modulation can also be done in an open-loop fashion, where initial measurements of beam current are performed prior to the implantation, instead of during. This would likely be based on some known non-uniformity in the system (*e.g.*, where a particular beam current results in a predicable non-uniformity). It will also be appreciated that while one use of such modulation is to achieve a uniform dosage on a wafer, it could be used to achieve any predetermined dopant profile, where uniformity is a subset of the general case.

Additionally, the beam current can be modulated to maintain or otherwise regulate a relatively constant beam current where the source output fluctuates. Thus, the beam current can be "trimmed" to lower the current where the output increases,

or to increase the current where the output decreases. The current can be increased, for example, by diverting, releasing or redirecting some rerouted or previously intercepted or stored beam current.

Referring now to Fig. 4, an ion implantation system 400 is illustrated wherein ion beam current may be modulated in accordance with one or more aspects of the present invention. The exemplary ion implantation system 400 is illustrated as having an ion source 402 for generating an ion beam 404. An extraction power supply 406 is included to bias a pair of extraction suppression electrodes 408, 410 (*e.g.*, to a potential of approximately 20 kV) to accelerate the ions from the source 402 along a trajectory leading to an ion mass analyzing magnet 412. The magnet 412 bends the beam 404 at approximately a right angle and directs ions having an appropriate mass along a travel path through a shutter 414. The shutter 414 rejects ions having an inappropriate mass from the ion beam 404.

The beam 404 then passes through a pair of deflection electrodes 416, 418. Control voltages applied to the electrodes 416, 418 by a control circuit 420 cause the ion beam 404 to pass through electric fields which deflect the ion beam 404 by a controlled amount. The magnitude of the voltage difference between the two plates 416, 418 controls the amount of deflection. A source of plasma 422 may also be included to bathe the beam 404 in neutralizing plasma to mitigate the number of positive charges that would otherwise accumulate on a target workpiece.

A beam accelerator 424 is also included to redirect ions along a travel path generally parallel to the trajectory they follow as they exit the analyzing magnet 412. The beam accelerator 424 includes a curved metallic entrance electrode 426 and a plurality of spaced, parallel metallic plates 428, 430, 432, 434. After passing through the accelerator 424 the ions in the beam 404 have been both redirected to a desired trajectory and accelerated to a desired implantation energy. The beam 404 generally travels in a vacuum maintained within a beamline assembly 436.

Downstream from the beam accelerator 424, an ion implantation station 440 includes one or more structures that support a semiconductor wafer 442 at a position to intercept ions that have been accelerated by the parallel plates 428, 430, 432, 434. Ion beam collisions with other particles degrade beam integrity so that the entire beamline assembly 436 from the source 402 to the implantation station 440 is evacuated by one or more pumps (not shown). At a region of the ion implantation station 440, a chamber 444 is similarly evacuated and the wafers are inserted into and withdrawn from load locks to avoid repeated pressurization and depressurization of the chamber 444.

A mechanized arm 446 located outside the chamber 444 grasps a wafer supported on a shuttle 448 that has obtained the wafer from a cassette 450. The arm 446 first positions each undoped wafer on a wafer orienter 456. The orienter 456 rotates the undoped wafer to a particular orientation before ion implantation so that as ions strike the wafer they encounter a specific orientation of the wafer's crystal lattice structure. The wafer is then moved into a load lock 458 so that a second arm 460 can move the wafers to an implant position within the chamber 444. At the implantation site a wafer support 462 orients the wafer 442 with respect to the ion beam 404 at a specific tilt angle that remains substantially constant.

The scanning electrodes 416, 418 produce side-to-side beam scanning of a controlled amount under the direction of the control circuitry 420. The circuitry may include, for example, a programmable micro-controller for adjusting the scanning electrode voltages to achieve desired wafer scanning. It will be appreciated that drive mechanisms (not shown) may also be attached to support 462 to facilitate additional relative motion between the ion beam 404 and the surface of the wafer 442. A measurement component 464 may be incorporated to monitor the beam current as the ion beam 404 is scanned across the wafer 442. This may include, for example, a Faraday cup and/or terminal return current, and can be utilized to

increase or decrease the ion beam concentration based upon a desired doping level for the silicon wafer 442 at the implantation station 440.

Once the wafer 442 has been doped by treatment with the ion beam 404, the wafer 442 is removed from the implantation station 440 by a third arm 466. This arm 466 delivers the wafer 442 to a load lock 468 so that a fourth mechanized arm 470 can transfer the wafer 442 to a shuttle 472 that moves the doped wafer 442 to a cassette 474.

It can be seen that the entrance electrode 426 of the accelerator 424 is constructed from an arcuate conductor. This electrode 426 is generally maintained at the same potential as a housing 476 which supports the source 402, the analyzing magnet 412, and the deflection electrodes 416, 418. The second electrode 428 is positively biased by a high voltage power supply 478. The voltage difference between the curved electrode 426 and the first generally planer electrode 428 is maintained by a lens power supply 480.

Representative voltages of approximately 60 kilovolts for the lens power supply 484, 20 kilovolts for the extraction power supply 406, and 120 kilovolts for the high voltage power supply 482 accelerate the positively charged ions to a final energy of approximately 200 keV. These voltages are appropriate for the illustrated implantation system 400 where the entrance electrode 426 has a radius of curvature of approximately 13 inches and which is spaced approximately 24 inches from the scan vertex at the position of the deflection electrodes 416, 418. An exemplary width of an entrance aperture defined within electrode 426 for this arrangement would be about 12 inches.

To generate ions, it will be appreciated that the ion source assembly 402 can utilize a cathode to create an arc discharge, or RF or microwave excitation, or electron beam injection, for example, to excite free electrons in the interior of an ion generation chamber. The electrons collide with gas molecules injected into the

chamber interior and ions are thereby generated. Ions may have an initial energy of between about 0.2 to 100 keV, for example, due in part to the effects of the extraction suppression electrodes 408, 410.

It will also be appreciated that the ion source 402 may include a source magnet to assist with generating ions. In the example illustrated, the source magnet includes multiple components 482, 484 that may, for example, correspond to a yoke 482 and coil 484 of an electromagnet. A set of ground electrodes 486 and an additional set of electrodes 488 are also included close to the source 402 to help focus and shape the beam 404 before entering the analyzing magnet 412.

Similarly, another set of electrodes 490, a set of plates 492 defining a resolving aperture and a subsequent set of electrodes 494 can be included to block spurious ions and provide focusing to the beam 404. A portion of the beam 404 can also be physically blocked to modulate beam current. For example, a mechanical structure (not shown) can be physically inserted (*e.g.*, through a slit 496 in beamline assembly 436) to selectively block some of the ion beam 404. Moving the mechanical structure in a prescribed manner to physically intercept some fraction of the beam current otherwise passing by would achieve the effect of modulating the beam current.

According to one or more aspects of the present invention, beam current can be modulated to achieve desired ion implantation by selectively controlling one or more components downstream of the ion source assembly 402, as well as one or more components more closely associated with the ion source assembly 402. For example, voltages applied to the deflection electrodes 416, 418, electrodes 490, plates 492 electrodes 494, and plates 426, 428, 430, 432, 434 of the beam accelerator 424 can be selectively regulated to modulate beam current (*e.g.*, *via* a controller, a measurement component and implantation waveforms as discussed above). Similarly, the extraction suppression electrodes 408, 410, ground electrodes

486, electrodes 488, source magnet components 482, 484 and the neutralizing plasma source 422 can also be selectively adjusted to modulate the beam current. Additionally, these elements can be selectively adjusted alone or in combination to desirably modulate beam current.

Turning to Fig. 5, a graphical representation 500 illustrates changes in beam current 502 as a function of changes in extraction suppression voltage 504 over time. It can be seen that changes in the beam current 502 closely track those of the extraction suppression voltage 504 over the approximately 100 second time period. In particular, the beam current 502 modulates between about 4.0E-03 to about 6.0E-03 Amperes while it tracks the extraction suppression voltage 504 modulating between about 7000 to about 10000 Volts.

Similarly, Fig. 6 is a graphical representation 600 illustrating a functional relationship between beam current (y-axis) and extraction suppression voltage (x-axis). The plot 602 reveals that changes in the beam current in response to changes in the extraction suppression voltage are a little more dynamic for voltages between about 6900 to about 8500 Volts where the beam current rather linearly goes from about 4.0E-03 to about 6.0E-03 Amperes. When the extraction suppression voltage goes from about 8500 to about 10000 Volts, however, the beam current hovers right around 6.0E-03 Amperes, indicating a saturation type condition.

It will be appreciated that the aspects described herein are equally applicable to primary electron beam current in “soft ionization” ion sources, RF or microwave power in RF or microwave ion sources, as well as to non-arc discharge sources.

Although the invention has been illustrated and described above with respect to a certain aspects and implementations, it will be appreciated that equivalent alterations and modifications will occur to others skilled in the art upon the reading and understanding of this specification and the annexed drawings. In particular regard to the various functions performed by the above described components

(assemblies, devices, circuits, systems, etc.), the terms (including a reference to a "means") used to describe such components are intended to correspond, unless otherwise indicated, to any component which performs the specified function of the described component (i.e., that is functionally equivalent), even though not structurally equivalent to the disclosed structure, which performs the function in the herein illustrated exemplary implementations of the invention. In addition, while a particular feature of the invention may have been disclosed with respect to only one of several implementations, such feature may be combined with one or more other features of the other implementations as may be desired and advantageous for any given or particular application. Furthermore, to the extent that the terms "includes", "including", "has", "having", "with" and variants thereof are used in either the detailed description or the claims, these terms are intended to be inclusive in a manner similar to the term "comprising". Also, the term “exemplary” as utilized herein simply means example, rather than finest performer.